The LIVING book

Chapter 1

The Composting Heap

Pass 1 — The Story

A pile that is alive

Behind the kitchen garden, at the edge of the field, there is a heap. From a distance it looks like nothing — a low mound of grass clippings, kitchen scraps, dry leaves, a few corn stalks bent over the top. If you walked past it without knowing, you might call it a pile of rubbish.

You would be wrong.

Put your hand on the heap. Not on top — push your fingers into the side, about an arm's length in. Hold them there.

It is warm.

Not warm like a stone in the sun. Warm like a sleeping animal. The heat does not come from outside. It comes from inside the heap, from somewhere deep in the middle, and it does not stop at night. Come back at midnight in the cold season and the heap is still warm. Come back in the rain and steam rises from it in thin white curls.

Something is happening in there. Something alive.

What we put in

Begin at the beginning. Six months ago, this heap did not exist. There was bare ground here, and a wooden frame, and nothing else.

Then we started adding things.

From the kitchen: potato peelings, carrot tops, onion skins, the outer leaves of cabbages, tea leaves, eggshells, banana peels, apple cores, the green tops of beetroots. Every day a small bucket. Wet, sweet-smelling, sometimes a little sour if it had sat too long.

From the garden: grass cuttings after every mowing, weeds we had pulled, the spent stalks of last season's beans, dead flowers, leaves raked from under the mango tree, twigs broken from pruning.

From the field: straw from the wheat harvest, husks from the maize, dry stalks of finished crops.

We put it all in layers. A layer of wet kitchen waste, then a layer of dry straw on top. Wet, dry. Wet, dry. Like building a cake. We sprinkled water when it got too dry, and added more straw when it got too wet. Every two weeks we turned the heap — pushing the outside in, the inside out, with a fork. That was all. We never added chemicals. We never added anything that did not once grow on a plant or come from an animal.

And now, six months later, the heap is warm.

What is inside

Take a spade. Cut into the heap from the side, slowly, the way you would cut into a cake to see the layers. Lift the spade out. Look at what you have.

At the top — the layer we added last week — you can still see what things used to be. There is a banana peel, brown now but still curled. There are grass clippings, faded yellow. There is a piece of cabbage leaf with a hole in it where a caterpillar once chewed. Everything is recognisable.

Dig deeper. About a hand's depth in. The colour darkens. The banana peel is gone — or rather, it has become something else, soft and brown and crumbling. The grass clippings have lost their shape: they look like tobacco, like dark threads. You cannot tell what the original things were. The smell is different too: not like rotting food, but like a forest floor after rain.

Deeper still. Two hands deep. The temperature rises sharply. If you have a thermometer, push it in and wait. The needle climbs. Thirty degrees. Forty. Fifty. In some heaps it reaches sixty-five degrees Celsius — hot enough that you cannot keep your hand pressed against it. This is the heart of the heap. Here, everything has dissolved into a dark, moist, steaming mass. You cannot recognise anything that was put in. It looks like wet, dark earth.

Deepest of all, near the bottom, where the heap has been working longest. The heat is gone here. The material is cool, almost cold. It is the colour of dark chocolate. It crumbles between your fingers. It smells sweet — the smell of the forest in spring. the smell of wet earth, a clean smell. It is no longer waste. It is something new.

It is compost. It is, in fact, soil. Or very close to it.

The disappearance

Here is the strange thing. The heap, six months ago, was much larger than it is now. We added many cartloads of material. By rights, the heap should be enormous. Instead it has shrunk to about a third of its starting size.

Where did the rest go?

You can see some of it. A thin trickle of dark water sometimes seeps out at the bottom — that is some of the moisture, carrying dissolved minerals into the ground below. The steam that rises in cold weather — that is water too, leaving as vapour. But this does not explain the bulk of what is missing. Cartloads of grass and kitchen scraps and straw. Where?

Most of it has left as gas.

When you breathe out, you exhale carbon dioxide. The carbon in that gas came from the food you ate. Inside your body, the food was broken down, and some of its carbon was combined with oxygen and breathed out into the air.

The heap is doing the same thing. Something inside the heap is eating the material we put in, and breathing out carbon dioxide and water vapour. The heap is breathing. That is why it is warm. That is why it shrinks. That is why it steams.

But the heap has no mouth. It has no lungs. It has no nose.

So what is breathing in there?

The small things

If you took a pinch of compost from the hot middle of the heap — just a pinch, less than would fit on the tip of a knife — and put it under a microscope, you would see them.

Bacteria, first. Millions of them. In a single gram of compost from the hot zone, there are more bacteria than there are people on Earth. Many more. They are everywhere, in every fold and crack of the rotting material. Some are shaped like rods, some like spheres, some like spirals. Most are too small to see even with a school microscope — you would need a more powerful one. But they are there.

Then fungi. You can sometimes see these without a microscope, especially in the cooler outer parts of the heap. Lift a piece of straw and look at its underside: thin white threads run across it, like cobweb. These are the bodies of fungi, called hyphae. Each thread is a single line of cells, growing forward, reaching into the material, digesting it.

Then larger creatures. Mites the size of a full stop. Springtails — tiny insects that jump when disturbed. Beetles. And, near the cooler outside of the heap, worms. Pink earthworms, but also smaller, paler worms called brandlings that love compost and live nowhere else.

All of them are eating. All of them are breathing. All of them are working.

A relay race

The heap is not eaten by all of them at once. It is eaten in turns.

When fresh material is added — soft, wet, full of sugars and proteins — the first to arrive are fast-growing bacteria. They love easy food. Within hours they begin to multiply. As they eat, they release energy. Some of this energy becomes heat. The heap warms up.

As more bacteria multiply, more heat is released. The heap warms further, faster. The temperature climbs from twenty degrees to thirty, to forty, to fifty. Now a different group takes over — bacteria that love heat. These bacteria can survive temperatures that would kill the first group. They are tougher, and they can break down materials the first group could not. The temperature climbs higher still, to sixty degrees or more.

This hot phase lasts for weeks. During this time, the heap is doing its hardest work. Weed seeds in the heap are killed by the heat. Disease-causing organisms are killed. Tough materials like straw and stalks, which the cool bacteria could not break down, are torn apart by the heat-loving bacteria and by fungi that have now joined them.

Then, slowly, the easy food runs out. The bacteria have fewer things to eat. Their numbers drop. Less heat is produced. The heap begins to cool.

As it cools, the heat-loving bacteria die back, and the original bacteria return — along with new ones, and many more fungi. They work on what is left: the toughest fibres, the hardest woody bits. This phase is slower and quieter. It can last for months.

By the end, almost everything that can be eaten has been eaten. What remains is the part of the original material that nothing can easily digest — a dark, stable substance called humus. This humus is what makes finished compost dark, crumbly, sweet-smelling, and good for the garden.

The relay is over. The heap is finished.

What it becomes

When we spread this finished compost on the garden beds, something quiet and important happens.

The compost is full of nutrients — nitrogen, phosphorus, potassium, calcium, magnesium, and dozens of others. Every nutrient that the original plants once contained is still there, in a new form, ready to be taken up by new plants. Nothing has been wasted. The carrot tops that went into the heap have become food for the new carrots that will grow this season.

The compost is also full of life. The bacteria and fungi that did the work of decomposition do not all die. Many of them go with the compost into the garden bed, and once there, they continue their work. They help the new plants by breaking down nutrients in the soil, by holding water, by protecting roots from disease.

The compost holds water. Sandy soil that drains too fast, mixed with compost, holds moisture for days longer. Clay soil that becomes hard and cracked, mixed with compost, becomes soft and crumbly. Compost improves any soil it touches.

And the carbon — much of the carbon from the original material is now locked into the humus. Some has escaped as carbon dioxide, yes, but a significant amount remains, stored in the soil, where it can stay for years. We will return to this point in a later chapter, because it matters a great deal for the planet.

What we have not yet asked

You can see now that the composting heap is not a pile of rubbish. It is a small living world, with its own seasons, its own communities, its own quiet drama. Six months ago, we put in waste. Today, we are pulling out something valuable.

But many questions remain unanswered.

Why does the heap heat up? Where exactly does the heat come from?

Why must we turn the heap? What goes wrong if we do not?

Why does a balance of wet and dry materials matter? What happens if we get the balance wrong?

What is happening, exactly, when bacteria eat? What chemical reactions are taking place?

Why do the same heaps that produce compost also produce a particular gas — sometimes methane, sometimes only carbon dioxide? What is the difference?

And the largest question of all: how is the decomposition in the heap related to the growth of plants in the garden? Are they opposites? Are they the same? Are they two halves of one larger process?

These are the questions of the next pass. We have seen the heap with our eyes. Now we will go inside it.

Pass 2 — The Mechanism

Decomposition is respiration in reverse direction, sort of

In your first biology lessons, you may have learned about photosynthesis. A green plant takes carbon dioxide from the air, water from the soil, and energy from sunlight, and combines them to make sugar. The plant releases oxygen as a by-product. The simplified equation is:

> $6\ CO_2 + 6\ H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$

The sugar is glucose. It is the basic chemical fuel of the living world. From glucose, plants build everything else: starch for storage, cellulose for cell walls, proteins (with the help of nitrogen from the soil), oils, vitamins. Every part of every plant that we eat traces back to this reaction.

Now consider what happens in the composting heap.

The material going into the heap was once plant tissue — leaves, stalks, fruits, roots, all built originally from glucose by photosynthesis. Inside the heap, bacteria and fungi are eating this material. They are pulling it apart, molecule by molecule, and using it for their own growth.

When a bacterium digests a molecule of glucose, it carries out a series of chemical reactions called respiration. The simplified equation is:

> $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$ + energy

Look at this equation. Now look back at the photosynthesis equation. They are mirror images. What photosynthesis builds, respiration takes apart. What photosynthesis stores, respiration releases.

The composting heap is, in essence, a slow-motion reversal of photosynthesis. The sugar that the original plants captured from sunlight is now being broken back down, releasing the energy that was once stored in it. That energy, in the heap, comes out as heat.

This is why the heap is warm. Every bacterium in the hot middle is carrying out millions of these reactions every second. Each one releases a tiny amount of energy. Multiplied by the billions of bacteria in a single gram of compost, and by the kilograms of material in the heap, the total heat is enormous — enough to keep the heap at sixty degrees for weeks.

But this is a simplification. Real plant material is not just glucose. It is a complex mixture: sugars, starches, proteins, fats, cellulose, lignin, waxes. Each of these is broken down by different organisms, by different reactions, at different rates. The full picture is more interesting than the equation suggests.

Who eats what

Plant material is not equally digestible. Some parts of it are easy food. Others are very hard food.

The easy food is the simple sugars and starches — found in fruits, soft leaves, kitchen scraps. These are short or moderately long chains of sugar molecules, and they can be taken apart by almost any decomposer. They are the first to disappear when fresh material is added to the heap. Within a few days, the sugars are gone.

Proteins are next. Plant proteins are chains of amino acids, and amino acids contain nitrogen. Bacteria are very interested in nitrogen, because they need it to build their own proteins (and DNA, and RNA). When bacteria digest plant proteins, they release some of this nitrogen, often as ammonia (NH_3) or ammonium (NH_4^+). If you have ever smelt a compost heap that has gone wrong — a sharp, eye-watering smell — that is

ammonia escaping. It means too much protein was added and the heap could not use it all. The nitrogen is being lost to the air.

Fats and oils take longer. They are energy-rich but require specific enzymes to break down. Some bacteria can do this; many cannot.

Cellulose is the structural material of plant cell walls. It is what makes a leaf hold its shape, what makes a stem stiff, what gives straw its toughness. Cellulose is a chain of glucose molecules — but bonded together in a way that most organisms cannot break. The enzymes needed to cut cellulose apart are called cellulases, and only certain bacteria and fungi produce them. This is why straw and stalks decompose slowly. They cannot be eaten until specialised organisms arrive to do the work.

Lignin is the toughest of all. It is the substance that turns soft plant tissue into wood. It is not really a chain at all but a complex, irregular network of carbon rings, very hard to disassemble. Almost no bacterium can digest lignin. The job is done almost entirely by certain fungi — the white-rot fungi and their relatives — which produce powerful enzymes that slowly, slowly tear lignin apart.

This is why the relay race exists. The fast bacteria eat the sugars first. Heat-loving bacteria then handle the more difficult materials. Fungi take their time with the cellulose and lignin. The order is determined by chemistry: who has the enzymes to do which job.

The carbon-to-nitrogen ratio

If a compost heap is the meeting place of millions of bacteria and fungi, what do they need to live? Two things above all: carbon, which is their energy and their building block, and nitrogen, which is essential for their proteins and genetic material.

A bacterium, in its body, has a particular ratio of carbon to nitrogen. Roughly, for every one nitrogen atom in a bacterial cell, there are about five carbon atoms. (The exact ratio varies, but five-to-one is a good rough figure.) This is the ratio bacteria are built from, and the ratio they need in their food.

But the food going into the compost heap does not come in that ratio. Different plant materials have very different ratios of carbon to nitrogen.

Fresh green grass clippings have a ratio of roughly 15 to 1 — fifteen parts carbon to one part nitrogen. This is rich in nitrogen for the bacteria: there is more nitrogen than they need.

Kitchen scraps are similar, around 15 to 1 or 20 to 1.

Dry leaves have a ratio of about 50 to 1.

Straw is around 80 to 1.

Sawdust is around 400 to 1 — almost pure carbon, hardly any nitrogen.

Here is the principle. The bacteria need their food at around 30 to 1 to work efficiently. (This is higher than their own body ratio because they also lose some carbon as carbon dioxide when they breathe, so they can use food with more carbon than is in their bodies.) If the ratio of the heap is much above 30 to 1 — too much carbon — bacteria run out of nitrogen and cannot multiply. Decomposition stalls. The heap stays cool. Straw left to itself, with no nitrogen-rich material added, can take years to break down.

If the ratio is much below 30 to 1 — too much nitrogen — there is more nitrogen than the bacteria can use. The surplus has to go somewhere. It escapes as ammonia gas, the sharp smell of a failed heap, and the nitrogen is lost to the air. The heap also tends to go anaerobic (we will come to this in a moment) and turn slimy.

This is why we build compost heaps in layers. A layer of grass (15 to 1, nitrogen-rich) and a layer of straw (80 to 1, carbon-rich) average out to something close to the ideal ratio. Wet and dry, green and brown, nitrogen and carbon — these are the same balance described in two different languages.

Oxygen and the air

A compost heap, working well, is full of air. The straw and stalks create gaps. The turning of the heap pulls fresh air into the middle and pushes spent air out. The bacteria need this air, because nearly all the bacteria doing the work in a healthy heap are aerobic — they require oxygen to breathe.

Aerobic respiration is the equation we saw earlier:

> glucose + oxygen → carbon dioxide + water + lots of energy

It is efficient. It releases a great deal of energy from each glucose molecule. Aerobic bacteria multiply fast and produce a lot of heat. The whole hot, fast-working middle of a healthy heap depends on them.

But what happens if a heap is too wet, or too tightly packed, and no air can reach the middle? The oxygen gets used up, and cannot be replaced. Aerobic bacteria die or go dormant. In their place, anaerobic bacteria take over — bacteria that live without oxygen.

Anaerobic respiration uses different chemistry. Without oxygen as the final acceptor of electrons, anaerobic bacteria must use other molecules. Some use sulphur compounds, and they produce hydrogen sulphide as a by-product — the smell of rotten eggs. Some use nitrates, releasing nitrogen gas. Some carry out fermentation, producing alcohols and acids. And a particular group, the methanogens, produce methane gas (CH_4).

An anaerobic heap is slow. It is slimy. It smells bad. It produces methane, which is a greenhouse gas roughly thirty times more powerful than carbon dioxide. From an ecological standpoint, an anaerobic compost heap is worse than no compost heap at all, because of the methane.

This is why we turn the heap. The turning is not for the look of the thing. It is to keep oxygen inside, to keep the bacteria aerobic, to keep the methane producers out. A well-turned, properly built compost heap produces almost no methane. A neglected, wet, compressed heap can produce a great deal.

Nitrogen, the most interesting atom in the heap

Of all the chemical elements in compost, nitrogen has the most complicated journey.

Plants need nitrogen to grow. They build it into proteins, into chlorophyll (the green pigment of leaves), into DNA. A plant with too little nitrogen has yellow leaves and grows slowly. A plant with enough nitrogen is green and vigorous.

But plants cannot use nitrogen directly from the air, even though the atmosphere is 78 percent nitrogen gas. The nitrogen in the air is N_2 — two nitrogen atoms triple-bonded together — and this bond is so strong that almost no living thing can break it. Plants take nitrogen from the soil instead, and only in particular chemical forms: ammonium (NH_4^+) or nitrate (NO_3^-).

When plant material decomposes in the compost heap, the nitrogen locked in plant proteins is released by bacteria. First it appears as ammonia (NH_3) and ammonium (NH_4^+). This is the form many plants can already absorb.

Then a particular group of bacteria — Nitrosomonas — converts ammonium to nitrite (NO_2^-). Another group — Nitrobacter — converts nitrite to nitrate (NO_3^-). This two-step process is called nitrification. It happens slowly, and it requires oxygen, so it happens mostly in the cooler, well-aerated parts of the heap and in the soil after the compost is spread.

The finished compost, then, contains nitrogen in several forms: still locked in undecomposed organic matter, partly in ammonium, partly in nitrate. When you spread the compost on the garden, plants begin taking up the nitrate and ammonium right away. The organic nitrogen continues to be broken down slowly over weeks and months, releasing more nitrate as it goes. This is why composted soil feeds plants for a long time, where chemical fertiliser flushes through in a few weeks: the compost is a slow-release source.

There is one more chapter of the nitrogen story. Some bacteria, called nitrogen-fixers, can take N_2 directly from the air and turn it into ammonium. They are the only living things that can break the triple bond of atmospheric nitrogen. Some live free in the soil; others live in the roots of leguminous plants (peas, beans, lentils, clover). Their importance to the farm — and to the entire living world — is so large that we will return to it in the chapter on roots.

The dance of carbon

We said earlier that much of the original mass of the heap leaves as carbon dioxide. Let us be more precise.

When a kilogram of fresh plant material is fully composted, roughly half of its carbon will be released to the atmosphere as carbon dioxide. The other half will remain — some in the bodies of the bacteria and fungi (who are themselves made of carbon), some in partially-decomposed organic matter, and some in humus, the stable end-product that resists further breakdown.

This humus is interesting. Once formed, humus is remarkably stable. It can persist in soil for decades, even centuries. The carbon in humus is, in effect, removed from the atmosphere for a long time.

This means that every well-managed compost heap is doing two things at once. It is releasing carbon to the air (through respiration) and storing carbon in the soil (through humus formation). The balance between these two — how much is released versus how much is stored — depends on how the heap is managed, on the materials used, on the climate, and on what happens to the compost after it is spread.

When we come to Chapter 7, on the soil, we will look at this carbon balance in detail. For now, hold the idea: the compost heap is not just turning waste into fertiliser. It is part of a much larger cycle, in which carbon moves between the atmosphere, the soil, and the bodies of living things — and the way we manage farms determines whether that cycle releases carbon to the air or pulls it down into the ground.

The principle that emerges

If you stand back from the heap and from all this detail, a principle begins to appear.

Decomposition and growth are not two separate things. They are two sides of one process — the cycle by which carbon, nitrogen, and other elements move through the living world. A plant grows by pulling carbon from the air and nitrogen from the soil. The plant dies, and decomposers pull the carbon back out (some to the air, some to the soil) and release the nitrogen for the next plant.

Photosynthesis builds. Respiration takes apart. The two processes, running side by side, are what makes life on the farm — and life everywhere — possible.

You cannot have one without the other. A world of pure photosynthesis would choke on its own dead bodies: nothing would be released back to the soil: the cycle would stop. A world of pure respiration is impossible — there would be nothing to respire. The two together are not opposites in conflict. They are partners in a single dance.

The compost heap, behind the kitchen garden, with its quiet warmth and its turning of waste into earth, is one small place where you can see both halves of the dance at once.

Pass 3 — The Mathematics and the Frontier

Measuring the heat

We said that the bacteria release energy as heat, and that this heat is what warms the heap. We can make this quantitative.

Consider a compost heap of one hundred kilograms (dry weight equivalent) of mixed plant material. Suppose this material is, on average, half carbon by dry mass. So the heap contains roughly fifty kilograms of carbon.

If the entire heap were fully respired — every carbon atom converted to CO_2 — the total energy released would be enormous. The energy released by respiring one mole of glucose (180 grams) is approximately 2,870 kJ. Glucose is forty percent carbon by mass, so one mole of glucose contains 72 grams of carbon.

Fifty kilograms of carbon is 50,000 grams. Divided by 72 grams of carbon per mole of glucose, that is roughly 700 moles of glucose-equivalent. Multiplied by 2,870 kJ per mole, the total energy potentially released is about 2,000,000 kJ — two gigajoules.

This is the energy of roughly fifty litres of petrol. It is the energy that ran the plants of the original material during their lifetimes — sunlight that they captured and stored. Now, in the heap, it is being released back, slowly, over months.

Of course, not all of this energy is released as heat. Some is captured by the bacteria themselves to build new cells. Some leaves as latent heat of water vapour (the steam). Some escapes through radiation from the surface of the heap. A working estimate is that about half the energy released by respiration is converted to sensible heat that raises the heap's temperature.

So one gigajoule, give or take, is available to heat the heap over six months. Spread across that time, this is an average power of about 60 watts — the power of a small light bulb, running continuously, for the duration of

the composting cycle. Concentrated in the middle of the heap, where the metabolism is most intense, the local power density is much higher, and this is why the centre can reach sixty-five degrees while the edges remain cool.

The rate equation

How fast does decomposition proceed? The simplest model is first-order kinetics: the rate at which material decomposes is proportional to the amount of material left.

> $dM/dt = -k\,M$

where M is the mass of decomposable material remaining, t is time, and k is the rate constant. The solution to this equation is:

> $M(t) = M_0\,e^{(-k\,t)}$

This means decomposition is exponential. Material decays fast at first (when there is a lot of it) and slows as it goes. A useful figure is the half-life — the time taken for half the material to decompose. For easy food (sugars, soft tissue), the half-life in a hot heap may be a few days. For cellulose, weeks. For lignin, months to years.

This is a simplification, because plant material is a mixture of substances with different rate constants. A more realistic model treats the heap as several pools:

> $M_{total}(t) = M_{easy}\,e^{(-k_1\,t)} + M_{medium}\,e^{(-k_2\,t)} + M_{hard}\,e^{(-k_3\,t)}$

where $k_1 \gg k_2 \gg k_3$. The easy pool disappears in days; the medium pool (mostly cellulose) over weeks; the hard pool (mostly lignin) over many months. The final humus is so resistant that, on the time-scale of a compost heap, its rate constant is effectively zero.

This three-pool model is a workhorse in soil science and is used today, in modified forms, to model carbon flows in agricultural soils and in climate predictions.

The rate constants themselves depend on temperature. As a general rule, biological rates roughly double for every ten degrees Celsius rise — the Q_{10} rule. So decomposition in a heap at sixty degrees runs perhaps eight to sixteen times faster than the same process at twenty degrees. This is why hot compost finishes in months while a cold pile of leaves at the foot of a tree may take years.

A worked example

Suppose you build a one-hundred kilogram heap in which the readily-decomposable fraction is fifty percent of the mass and has a half-life of seven days at the prevailing average temperature, and the slowly-decomposable fraction is thirty percent with a half-life of seventy days. The remaining twenty percent is the resistant fraction with a half-life so long we can treat it as constant within the scope of this calculation.

How much mass remains after one month (thirty days)?

For the readily-decomposable pool: M_0 = 50 kg, t = 30 days, half-life = 7 days, so the decay constant $k = \ln(2)/7 \approx 0.099$ per day. $M(30) = 50 \times e^{(-0.099 \times 30)} \approx 50 \times e^{(-2.97)} \approx 50 \times 0.051 \approx 2.6$ kg.

For the slowly-decomposable pool: M_0 = 30 kg, t = 30 days, half-life = 70 days, so $k = \ln(2)/70 \approx 0.0099$ per day. $M(30) = 30 \times e^{(-0.0099 \times 30)} \approx 30 \times e^{(-0.297)} \approx 30 \times 0.743 \approx 22.3$ kg.

The resistant pool stays at 20 kg.

Total remaining mass after thirty days: about 2.6 + 22.3 + 20 = 44.9 kg.

Original mass: 100 kg. Mass lost in one month: about 55 kg. Most of this leaves as carbon dioxide and water vapour; a small fraction trickles out as leachate or remains as bacterial biomass within the heap.

This matches what you observe: a heap loses roughly half its mass in the first month or two of vigorous decomposition, and the rest disappears more slowly.

The temperature curve

If you plotted the temperature of the heap day by day, what would the curve look like?

In the first day or two, the temperature rises rapidly, perhaps from 20 °C to 50 °C, as the readily-decomposable pool is attacked. The temperature then climbs more slowly to a peak — typically 60 to 65 °C — which is reached after three to ten days, depending on heap size and conditions. The plateau lasts for one to three weeks, during which the heat-loving bacteria dominate. After this, as the easy food runs out, the temperature begins to decline, slowly at first and then faster. By six to eight weeks, the heap is typically at 30 to 40 °C; by three to six months, it is back to near-ambient temperature, and decomposition is complete or nearly so.

This curve — fast rise, plateau, gradual decline — is the signature of a system limited first by reaction rate (warming up as bacteria multiply), then by substrate availability (running out of easy food). Similar curves appear in many biological systems: the growth of a bacterial culture in a flask, the rise and fall of a population of insects in a field, the burning of a fire as it goes through its fuel.

Once you have seen the temperature curve of a compost heap, you have seen the general shape of how living systems consume a finite resource.

Stoichiometry and the C:N ratio, sharpened

Earlier, we said that a C:N ratio near 30:1 is optimal for composting. This is a rule of thumb. The underlying principle is more exact, and it is worth a closer look.

The bacterial cell, as we said, has a C:N ratio of roughly 5:1 in its own biomass. When bacteria digest organic matter, some of the carbon they take in goes into building new cells (call this fraction Y, the yield), and the rest is respired as CO_2 (fraction $1-Y$). The yield Y for aerobic bacteria on plant material is typically around 0.3 to 0.4 — that is, thirty to forty percent of the carbon ends up in bacterial biomass, the rest is respired.

If bacteria need nitrogen at 5:1 in their biomass, but only one-third of the carbon they take in becomes biomass, then for every five carbon atoms in their food, they need one nitrogen atom in their food only if Y were 1. If Y is one-third, they only need one nitrogen for every fifteen carbons they consume. But not all consumed carbon ends up in the cell — so for every nitrogen, they can process about three times more carbon

than the simple 5:1 ratio would suggest. This is why the food ratio of 30:1 works for bacteria with a body ratio of 5:1.

When the food ratio is much higher than 30:1, bacteria are starved for nitrogen. They multiply slowly, even if there is plenty of carbon to burn. When the ratio is much lower than 30:1, bacteria have surplus nitrogen — more than they can use in their cells — and excrete the excess as ammonia, which escapes to the air.

Now you can predict what will happen with any compost recipe. Take a mixture of materials, look up their C:N ratios, calculate the weighted average for your heap. If the result is well above 30, the heap will be slow: if well below, the heap will lose nitrogen and smell bad. The closer to 30, the more efficient the process and the less waste of either resource.

An open question for you

Here is a question to which the textbook does not have a complete answer.

A compost heap built from exactly the same materials, in exactly the same proportions, in two different climates — say, a hot dry climate and a cool humid one — will produce compost with different chemical and biological compositions, even after both have run to apparent completion. Why?

Part of the answer involves which bacteria and fungi are locally abundant. Part involves how the temperature curve plays out (a heap in a hot climate may run hotter and shorter; one in a cool climate may run cooler and longer, favouring different microbes). Part involves rainfall: more rain washes more nitrate downward, leaving the finished compost different.

But the full answer is genuinely a research question. Soil scientists working today on compost composition use isotope labelling, high-throughput DNA sequencing of microbial communities, and chromatography of dissolved organic matter to try to characterise the differences. The compost from your school garden and the compost from a school garden two thousand kilometres away are not the same product, even if the recipe is identical.

This is an opening, not a closing. The composting heap, simple and ancient, still has things to teach the people who study it most carefully.

Connecting to climate

We have left the largest topic for last.

Agriculture, world-wide, contributes roughly one-quarter of all greenhouse gas emissions to the atmosphere. Most of this comes from deforestation, livestock, synthetic fertiliser production, and the burning of crop residues. A significant fraction also comes from soil degradation: when soils lose organic matter, the carbon they once held returns to the atmosphere as CO_2.

Composting reverses this. A heap that produces stable humus, and that humus is then incorporated into soil, removes carbon from the atmosphere and stores it underground. A hectare of farm, well managed, can build perhaps half a tonne to one tonne of soil carbon per year, sustained over decades. Multiplied across the agricultural land of a country or a continent, the numbers become significant in the global carbon balance.

This is not a complete solution to climate change. The numbers involved in fossil fuel burning are larger than what agriculture alone can offset. But it is a contribution, and it is one of the few contributions that simultaneously feeds people, improves soil, reduces fertiliser dependence, and pulls carbon from the air. Few solutions do all of these at once.

In the chapters that follow, we will return to this theme — in the soil chapter, where we look at how carbon and nitrogen move through the underground ecosystem; in the year chapter, where we look at the farm as a whole over a full annual cycle; and in the closing chapter, where we step back and ask what kind of farm could be built, given everything we have learned.

For now, the lesson of the compost heap is enough on its own. A pile of waste, given time and air and a little attention, becomes earth. The hands that turn the heap with a fork are part of a process that began with sunlight and that will continue with the next plant to grow on this land.

Exercises

The exercises are grouped by level. Take what fits where you are; return to harder ones when you are ready.

Level A — Observation and basic understanding

1. Describe in your own words what you would see, smell, and feel if you broke open a six-month-old compost heap at three different depths.

2. List at least eight different kinds of material that can go into a compost heap, and group them into "wet/green" and "dry/brown" categories.

3. A heap is described as "alive". Explain what this means without using technical terms.

4. Why does a compost heap shrink in size as it works?

5. Name three different kinds of living things you would find in a compost heap, and describe what each one does.

6. What is the difference between fresh compost (one week old) and finished compost (six months old) in terms of appearance and smell?

Level B — Mechanism and reasoning

7. Write the equation for photosynthesis and the equation for aerobic respiration. Explain in two or three sentences how the compost heap connects them.

8. Explain why a compost heap heats up in the middle but not at the edges. Use the words "bacteria", "energy", "respiration".

9. The C:N ratio of fresh grass is about 15:1, and that of straw is about 80:1. A compost heap is built using 30 kg of fresh grass and 20 kg of straw. Estimate the overall C:N ratio of the mixture. Is it close to the ideal? Show your reasoning.

10. A farmer adds a great deal of fresh kitchen waste to a heap but no straw or dry material. After a few days the heap is wet and smells of ammonia. Explain what has gone wrong, in terms of the C:N ratio and oxygen.

11. Why does a compost heap need to be turned every two weeks? What would happen biologically if it were never turned?

12. A compost heap left in the rain, untouched, eventually produces methane. Explain why, and explain what is different from a heap that is regularly turned.

13. Nitrogen passes through several forms in a compost heap: organic nitrogen in plant proteins, ammonium, nitrite, nitrate. Draw a diagram showing this sequence and label which bacteria are responsible for each conversion.

Level C — Quantitative and exploratory

14. Using the three-pool decomposition model described in Pass 3, calculate the mass remaining after sixty days for a 200 kg heap in which 40% is readily decomposable (half-life 10 days), 40% is slowly decomposable (half-life 80 days), and 20% is resistant. Plot the mass-remaining curve at ten-day intervals.

15. The Q_{10} rule states that biological rates roughly double for every 10 °C rise in temperature. If a particular decomposition reaction has a half-life of 14 days at 20 °C, estimate the half-life at 50 °C. State the assumptions you are making and where they might break down.

16. A 100 kg compost heap loses about half its mass over six months, of which most leaves as CO_2. Estimate how much carbon, in kilograms, is released to the atmosphere from this single heap. (Assume the heap is 50% carbon by dry mass and that of the lost mass, 90% is carbon-containing gases and water.) Then estimate the carbon stored in the remaining humus.

17. A school operates a composting programme that processes 500 kg of kitchen waste per month from its cafeteria. Over a year, what total mass of finished compost would the school produce, assuming a 50% mass loss during composting? If this compost is spread on the school garden at 5 kg per square metre, how large a garden can the school's compost support?

18. Read about the Lotka–Volterra equations (predator–prey dynamics). Now consider the bacterial population in a compost heap during the hot phase: bacteria are the "prey" of their own running out of food. Sketch a simple system of equations that could describe how bacterial mass and substrate mass change over time. Solve qualitatively: what does the curve of bacterial population over time look like, and when does the peak occur?

19. Research project. Design and run a comparison: build two small compost heaps with the same materials but different C:N ratios (one near 30:1, one well above 60:1). Measure the temperature daily for six weeks. Plot both curves on the same axes. Write a short report explaining what you observed and how it confirms or complicates the discussion in Pass 2.

20. Open question. The text states that compost from two different climates, made from identical recipes, will be chemically and biologically different. Choose one specific factor (rainfall, temperature, native microbial community) and propose an experiment that could quantify how much that factor alone changes the final compost. What would you measure, and what would your result mean?

Activity — Build a heap

If you have access to a garden, a school yard with a corner, or even a large container with drainage, build a compost heap. Keep a daily journal for at least eight weeks: temperature, smell, what was added, what was

observed. At the end, compare your notes to the temperature curve described in Pass 3. Where did your heap match the model? Where did it diverge? What might explain the differences?

Chapter 2: The Seed — coming next.*

Chapter 2

The Seed

Pass 1 — The Story

Three seeds in the palm of a hand

Hold out your hand. Place three seeds in your palm.

The first is round, the size of a small marble, the colour of pale honey, with a small dark dot where it was once joined to its pod. A chickpea. In Hindi, *chana*. It feels heavy for its size. It is hard. If you tried to crush it between finger and thumb, you could not.

The second is much smaller — the size of a peppercorn, but rounder and darker. A mustard seed. *Sarson*. Roll it between your fingertips. It has a slight shine. There are dozens like it on your palm if you tip the rest of the small heap in: one alone almost disappears.

The third is somewhere between the two in size, but very different in shape — oblong, slightly pointed at one end, smooth, grey-green. A pearl millet seed. *Bajra*. It feels light, almost papery, compared to the chickpea. If you bite it (gently) it is harder than the mustard but not as dense as the chana.

Three seeds. Three different sizes, three different colours, three different feels in the hand. And three different lives waiting to begin.

The chickpea will be sown in November, when the monsoon is long past and the days are short and cool. It will grow through the winter, flower in February, and be ready to harvest in March. It belongs to the *rabi* season — the winter crop.

The mustard will be sown at almost the same time, in October or November, also a rabi crop, also a winter grower. By February the field will be a sea of small yellow flowers. By March, the pods will be ripe.

The bajra will not be sown until June or July, when the monsoon arrives. It will grow through the rains, tolerate the heat that would kill the chickpea and the mustard, and be ready to harvest by October. It belongs to the *kharif* season — the monsoon crop.

In one farmer's field, in one year, all three seeds will be planted. But not at the same time, and not in the same way. The seeds themselves know which season they belong to. The farmer who hands them down through generations knows which seed waits for which month. The calendar of the field has been written in seeds for as long as people have farmed this land — perhaps eight thousand years on the plains of North India, where chickpea was domesticated, and longer still in the Sahel, where bajra began.

What a seed contains

Pick up the chickpea again. It is the largest of the three, the easiest to study.

Soak it overnight in water. By the morning, it has changed. It has doubled in size. Its skin has wrinkled in some places and stretched in others. It is no longer hard: you can press it now between finger and thumb, and it gives.

Peel back the skin. It comes away in two pieces — a thin papery covering called the *seed coat* or *testa*. Underneath is what looks like a soft yellowish lump.

Now gently split this lump in half. It comes apart easily: the two halves were always two halves, held together. These are the *cotyledons* — the seed leaves. Each is plump, soft, full of stored food. If you taste a tiny piece, it is starchy and a little nutty. This is what the seedling will eat before it can make its own food.

Look closely at where the two cotyledons join. There, in the crease, you will see a tiny pale structure no bigger than a grain of rice. This is the *embryo* — the seedling-in-waiting. It has a tiny pointed end (the *radicle*, which will become the root) and another, smaller end (the *plumule*, which will become the shoot). The whole future plant — its roots that will go down two metres, its stem that will hold up dozens of pods, its leaves that will catch the winter sun — is folded inside this rice-grain-sized embryo.

A seed, then, is not a single thing. It is three things, neatly packed:

A protective covering — the seed coat — to keep the embryo safe from drying out, from being eaten, from being attacked by microbes, from beginning too early.

A store of food — the cotyledons, in the chickpea — to feed the embryo until it can feed itself.

The embryo itself — the next generation, asleep, waiting.

Now look at the mustard seed under a hand lens or a simple microscope. It is the same three things, much smaller, and the food store is held differently — in a tissue called the *endosperm* that surrounds the embryo rather than inside cotyledons. (The cotyledons in mustard are tiny, barely visible.) Different design. Same purpose.

And the bajra? Bajra is a *monocot* — a different kind of plant altogether from chickpea and mustard. Inside the seed coat there is a large endosperm, mostly starch, and a small embryo at one end with a single cotyledon (called a *scutellum* in grasses) pressed against the food store. When bajra germinates, the food does not move into the cotyledon and then to the seedling — it stays in the endosperm, and the cotyledon absorbs it gradually, passing it on.

Three seeds, three internal designs. But the same three parts, in different proportions, doing the same work.

Sleep

Here is the most remarkable thing about a seed.

The chickpea on your palm could have been harvested last March, fifteen months ago. It has sat in a sack, in a steel drum, in a kitchen tin, since then. For fifteen months it has not grown. It has not even, as far as you could see, breathed. And yet it is alive.

If you had cracked open this same chickpea two days ago, you would have found the embryo inside — the same tiny structure, the same pointed radicle, the same folded plumule. It is not dead. It is not dormant in the sense of being unconscious. It is *waiting*.

A seed in this state is doing something a leaf cannot do, an animal cannot do, almost no other living thing can do. It is alive but it has slowed its life almost to a stop. Its water content has dropped to perhaps ten percent of fresh tissue (a leaf is ninety percent water). Its metabolism — the chemical reactions that keep it alive — has slowed by a factor of thousands. It can survive temperatures that would kill the parent plant. It can survive being eaten by a bird and passing through the bird's gut. Some seeds can survive being buried for decades. Lotus seeds have been germinated successfully after a thousand years.

This state has a name. It is called *quiescence* when the seed is simply waiting for the right conditions, and *dormancy* when something inside the seed actively prevents germination even when conditions seem right. Many seeds have built-in dormancy as a safety device — they will not germinate immediately even if water and warmth are provided, because the parent plant has, in effect, decided that this is not the right season. Mustard seeds shed in April will not germinate in May, even if it rains, because they are dormant. They wait for the cold of November before they will respond. By then, they have forgotten April — the dormancy has worn off, the timer has run down. Now, when water arrives, they wake.

How does a seed know what time of year it is, when it has no eyes, no clock, no calendar?

It feels temperature. It senses moisture. Some seeds detect light — the colour of the light, the length of the day. Some need to be chilled for weeks before they will germinate (this is why apple seeds need a cold winter: without one, they stay asleep). Some need to pass through fire. Some need to be physically scratched (passed through an animal's gut, or scraped by sand and stone). Each species has evolved its own set of triggers — its own way of knowing.

The bajra seed in your palm has been waiting since last October. It does not have deep dormancy — bajra is quick to germinate once given water — but it does need warmth. If you sowed it in January, in cold soil, it would barely respond. By June, when the soil is hot and the first monsoon rains arrive, it will sprout within days.

The chickpea is the opposite. It wants the cool of November. Sow it in May and the heat will damage it. Sow it in November and within a week the field will be green.

Each seed remembers, in some way, the season of its parents. Each seed is keyed to a particular time of year. The farmer who knows the seeds also knows the calendar — but only because the seeds taught it to him, generation after generation.

The awakening

Now we take the soaked chickpea, and the moistened mustard seed, and the bajra wrapped in damp cloth, and we watch.

The chickpea is the easiest to observe. Within a day of soaking, something has changed inside. The seed is now plump, fully hydrated. Its cotyledons are taking up water. The embryo, which had been almost completely dry, is now wet enough that its chemistry can begin.

By the second day, the radicle — the future root — has begun to push out. It emerges from a small split in the seed coat, near the dark dot where the seed was once attached to its pod. The radicle is pale, almost white, and it grows downward, drawn by gravity. Within another day it is a centimetre long.

By the third day, the plumule — the future shoot — has begun to extend in the opposite direction. The two cotyledons remain inside the seed coat for now, slowly being emptied as the seedling draws on their food. The radicle, meanwhile, has branched: small lateral roots are beginning to spread.

By the end of the first week, if the chickpea is planted in moist soil, you would see the shoot break the surface. A small pale loop emerges first, pulling itself up through the soil; then the first two true leaves unfold, green, ready to begin photosynthesis. The cotyledons by now are nearly empty, shrunken, doing the last of their work.

The mustard seed runs the same race much faster. From dry seed to sprouted seedling: two or three days. The plant is in a hurry; it has a small store of food, and it must reach light quickly or it will starve.

The bajra, given warmth and water in June, takes about three to four days to show its first shoot. Because it is a grass, the shoot looks different — a single narrow blade pushing up, a long thin root pushing down. No paired cotyledons spread above the ground. The food store in the endosperm is being drawn down through the scutellum, feeding the seedling as the first green leaf reaches the air and begins to do its own work.

In all three, the same drama: water arrives, dormancy breaks, the embryo wakes, the food store empties, the root reaches down, the shoot reaches up. The seedling has perhaps a week to a fortnight before its stored food runs out. By then it must be photosynthesising. Otherwise, it dies.

A seed is a promise

There is something to notice before we leave this first pass.

The chickpea you held in your hand was made by another chickpea plant. That plant was made by another chickpea plant, grown the year before. That one, by another. Tracing the line back: every chickpea seed alive today is the descendant of every chickpea seed that came before, in an unbroken chain reaching back to the first chickpea plant ever domesticated in the Fertile Crescent, perhaps eight thousand years ago. And before that, back to the wild ancestor, *Cicer reticulatum*, growing on hillsides in what is now Turkey.

Every seed is, in this sense, a message from the past. The information needed to build a chickpea plant — the colour of its leaves, the shape of its pods, the time at which it should flower, the foods it stores in its cotyledons — has been carried in seeds, from parent to seed to seedling to parent, for thousands of years.

This information is held in the DNA inside the cells of the embryo. We will come to DNA in the chapter on variety. For now, simply notice: a seed is small, but the information it carries is large.

It is also a promise. A promise that, given the right season, the right soil, the right water, this small dry thing will become a plant — and that plant will, in its turn, make seeds. The cycle of the field is older than any farmer working in it. The seed is the link between one season and the next, between one generation and the next, between one century and the next.

In the next pass, we go inside the seed. We will look at the chemistry of the food stores, the biology of dormancy, the hormones that wake the embryo, and the rate at which water moves into a dry seed once it is placed in damp soil.

Pass 2 — The Mechanism

Imbibition: the seed drinks

The first thing that happens when a dry seed meets water is purely physical. The seed coat and the dry tissues inside are porous: they contain proteins, starches, and cellulose, all of which can absorb water by simple wetting. Water molecules are drawn into the seed by *imbibition* — a process that does not require the seed to be alive at all. A dead seed will imbibe water just as readily as a live one.

Imbibition can be remarkably forceful. A dry chickpea, swelling as it takes up water, exerts pressures that can crack open soil crust and lift small stones. In some seeds, the swelling itself splits the seed coat, allowing the radicle to emerge. The forces involved are measured in the same units as steam pressure in an engine: imbibition pressures of several atmospheres are common.

The phase of imbibition lasts only a few hours in most seeds. The seed reaches a water content of roughly 60 percent fresh weight — comparable to a living leaf — and the rate of further water uptake slows sharply. The seed has rehydrated. Its cells, which had been almost dry, are now full of liquid water again. Membranes that had been folded and rigid become flexible. Enzymes that had been locked in inactive form can now move. Chemistry can begin.

Metabolism resumes

The seed has been alive throughout its dormant period, but very slowly. As water content rises, the rate of biochemical reactions inside the seed cells rises with it — not linearly, but steeply. A seed at 10 percent water content has a metabolic rate hundreds or thousands of times lower than the same seed at 60 percent. The relationship is not simple, but the general direction is clear: water enables life, dry tissue suspends it.

Within hours of imbibition, the seed begins to respire. The mitochondria in its cells — which were intact but dormant — begin to consume oxygen and release carbon dioxide. The rate of respiration climbs rapidly. A germinating seed at 25 °C may be respiring as fast, per gram of dry weight, as the leaves of an active plant.

This respiration is the same aerobic respiration we met in Chapter 1, in the compost heap. The seed is now burning some of its own stored food to power its awakening:

> $C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{energy}$

The energy released is used to drive the chemistry of germination: to break down stored food into mobile sugars, to rebuild proteins, to start cell division in the embryo. A small amount of this energy is also released as heat — far less than in the compost heap, because the number of cells is small, but enough that a sealed jar of germinating seeds will warm by a degree or two.

There is a point worth holding here. The same chemistry is doing different work in different places. In the compost heap, respiration tore plant tissue apart into CO_2 and water and heat. In the seed, respiration breaks down stored food to release the energy needed to build a new plant. The reaction is the same. The purpose, in the broader story of the farm, is opposite.

Mobilising the food store

The chickpea has stored most of its food in the two cotyledons. The food is not in a form the seedling can use directly. It is in the form of:

- *Starch*: long chains of glucose molecules, tightly packed for storage. About 50 percent of the dry mass of a chickpea cotyledon.

- *Protein*: chains of amino acids. About 20 to 25 percent — high for a plant seed, which is why chickpeas are an important food.

- *Oils*: fats, less common in chickpea but very common in mustard, which is about 40 percent oil by weight. Bajra is intermediate.

None of these can be transported through the seedling's tissues. They must be broken down into smaller, mobile molecules first.

Starch is broken down by enzymes called *amylases*, which cut the long chains into glucose units. Within days of imbibition, amylase activity inside the chickpea cotyledons rises sharply. Glucose is released. This glucose moves out of the cotyledons through the small vascular connections to the embryo, where it is used both as food for cell division and as raw material for building new tissues.

Protein is broken down by *proteases* into amino acids. These amino acids move to the embryo and are used to build the proteins of new cells.

Oils — especially important in mustard — are broken down by *lipases* into fatty acids and glycerol. The fatty acids are then converted into sugars through a remarkable chemical pathway called the glyoxylate cycle, which occurs only in seedlings and in some microorganisms. (The seedling, in effect, turns its stored fat into sugar — something an animal cannot do.)

This mobilisation of food is itself a major part of germination. It requires the synthesis of large amounts of new enzyme. The genes coding for amylase, protease, and lipase, which had been silent in the dry seed, are switched on within hours of imbibition. The seed is, in a chemical sense, waking up its own factories.

Hormones: the signals that switch genes on

How does a dry chickpea, sitting in moist soil, decide that it is time to germinate? The signal that starts the process — and that controls its timing — is carried by *hormones*.

A plant hormone is a small molecule, produced in tiny amounts, that travels short distances and triggers large changes in the cells it reaches. Two hormones matter most for germination:

Gibberellin is the awakening hormone. As the seed imbibes water, gibberellin is synthesised in the embryo. It moves out to the surrounding food storage tissue (the cotyledons in chickpea, the endosperm in bajra and mustard) and switches on the genes that produce digestive enzymes — amylase, protease, lipase. Without gibberellin, germination stalls. With it, the food store is mobilised, and the seedling grows.

Abscisic acid is the opposite — the sleeping hormone. While the seed is developing on the parent plant, abscisic acid accumulates in the embryo and forces it into dormancy. As long as abscisic acid levels are high, gibberellin cannot do its work. The seed sleeps.

The balance between these two hormones is the seed's clock. As the seed ages on the shelf, abscisic acid slowly degrades. The dormancy weakens. By the right season, the balance has shifted enough that water and warmth can trigger gibberellin production, and the seed germinates.

In some seeds, environmental signals shift the balance directly. Cold temperatures degrade abscisic acid quickly; this is why apple seeds need winter chilling. Light triggers gibberellin synthesis in some species, which is why certain seeds will only germinate when they are at or near the soil surface, where light reaches them.

For the three seeds in your hand, the cues are different but the underlying mechanism is the same:

The chickpea uses temperature primarily. It germinates best between 15 and 25 °C — the cool soil of post-monsoon North India. At 35 °C, it germinates poorly. The high temperature interferes with the balance of hormones and damages the enzymes.

The mustard uses temperature too, but in the opposite direction. It germinates best in cool weather, after the soil has cooled below 20 °C, but it does not germinate well in deep winter cold either. The window is October to early December in North India.

The bajra waits for heat. It germinates best between 28 and 35 °C, in moist soil — the conditions of the early monsoon, when the soil is warm from the summer and the rains have begun.

The four stages of germination

We can now describe germination as a sequence of four overlapping stages.

Stage 1: Imbibition. The dry seed takes up water. Duration: hours. Driven by physical wetting and osmosis. The seed swells, the seed coat softens, membranes rehydrate.

Stage 2: Activation. Metabolism resumes. Respiration begins, hormones are synthesised, dormant enzymes become active. Duration: hours to a day. The seed is now living at a normal rate.

Stage 3: Mobilisation. Stored food is broken down into mobile molecules and transported to the embryo. New enzymes are produced. The embryo begins cell division. Duration: one to several days. The radicle elongates and emerges through the seed coat.

Stage 4: Establishment. The seedling grows. The radicle extends into the soil and begins to absorb water and minerals. The shoot extends upward toward light. The first true leaves expand, and photosynthesis begins. The cotyledons (or endosperm) progressively empty. Duration: one to two weeks. By the end, the seedling is autotrophic — feeding itself — and the seed is finished.

The transition from Stage 3 to Stage 4 is the critical one. Until the first green leaf opens and begins photosynthesising, the seedling is entirely dependent on the food the parent plant provided. If germination is delayed, or if the seedling cannot reach light fast enough, the stored food runs out and the seedling dies. This is why depth of sowing matters so much. A chickpea sown ten centimetres deep may exhaust its reserves before the shoot reaches the surface; sown two centimetres deep, it emerges easily.

Seedlings of different kinds

The three seedlings, once they emerge, look strikingly different from each other.

The chickpea is a dicotyledon: two seed leaves, soft and pale, that may emerge above the ground or remain below it. (Chickpea is *hypogeal* — the cotyledons stay underground.) Above them, on a thin stem, the first true leaves expand. These are recognisably chickpea leaves from the start: small, oval, in opposite pairs along a central rib.

The mustard, also a dicot, is *epigeal* — its two small cotyledons are lifted above the ground by the elongating stem. The cotyledons are themselves green and photosynthetic in mustard, providing food until the true leaves expand. The first true leaves of mustard are spoon-shaped, lightly lobed, on a slender stem.

The bajra, a monocot, sends up a single narrow blade — the first leaf, rolled up like a tube as it pushes through the soil, then unrolling. There are no cotyledons visible. Behind the first leaf, more leaves emerge in succession, each from inside the previous one. The young bajra plant is recognisably a grass from the start.

These differences are not surface decoration. They are signatures of two great branches of the flowering plants — the *monocots* (grasses, palms, lilies, orchids, all the cereals including rice, wheat, bajra, maize, ragi, sugarcane) and the *dicots* (legumes, mustards, tomatoes, cottons, most of the trees we see). The split between these two groups happened more than 100 million years ago, long before any human walked the earth. Every seed you have ever sown belongs to one or the other.

For the farmer, the difference matters in practice. Monocots have fibrous root systems — many roots of similar size, spreading horizontally. Dicots have a tap root with branches — a deep primary root with smaller laterals. The way monocots and dicots draw water from the soil is different. The way they respond to drought is different. The way they need to be fertilised is sometimes different. We will return to this in Chapter 4.

Why three seasons, three seeds

Now we can answer a question raised in Pass 1: why does the chickpea wait for November while bajra waits for June?

The answer is partly history and partly physics. Bajra evolved in the Sahel, on the southern edge of the Sahara — a place of intense heat and brief monsoon rain. Its ancestors were grasses adapted to grow fast in warm wet conditions and to survive the long dry season as dormant seed. When humans began domesticating bajra perhaps 4,500 years ago, they selected from these grasses. The seeds inherited the timing of their wild ancestors: warm soil, monsoon rain, fast growth.

Chickpea evolved in the cool hills of the Fertile Crescent — what is now Turkey, Syria, northern Iraq. Its wild ancestor grew through the mild winter and matured in spring, before the summer heat. Chickpea seeds inherited that timing. When chickpea travelled to India, perhaps 4,000 years ago, it found a season that matched: the cool rabi, after the monsoon, before the summer heat.

Mustard travelled from a similar place — central Asia, with cool winters and warm dry summers. It too became a rabi crop.

The Indian farming calendar is, in part, the inheritance of seeds from many origins, each placed into the season that matches the temperatures of its homeland.

This is not just botanical curiosity. It is the deep architecture of Indian agriculture. The double-cropping system — kharif in the monsoon, rabi in the winter — uses the natural alternation of warm and cool seasons to grow two different sets of crops on the same land each year. The system works because the seeds came from different climates and never had to compete with each other. Bajra grows in warmth that would kill mustard. Mustard grows in cool that would not even wake bajra. Together, they fill the year.

The principle that emerges: the timing of every crop in the field is not a human decision. It is a botanical one, made tens of thousands of years ago in a different climate, carried in the dormancy-and-germination chemistry of every seed sown. The farmer who chooses when to sow is reading a script written by the seeds themselves.

In the next pass, we treat germination quantitatively — water uptake curves, rate of respiration, hormone concentrations, and the energy budget of a seedling drawing on its food store.

Pass 3 — The Mathematics and the Frontier

The water uptake curve

When a dry seed is placed in water, its water content rises with time. The curve has a characteristic shape: rapid uptake in the first few hours (Phase I — pure imbibition), a plateau lasting from several hours to a day during which water content stays roughly constant (Phase II — metabolic activation, with little net change in water), and then a second rise as the embryo grows and cells expand (Phase III — growth).

This three-phase curve was first described in the 1970s by the seed physiologist J. Derek Bewley, and it is the standard textbook account of germination water uptake to this day. The plateau of Phase II is biologically the most interesting: this is when the seed has hydrated enough for metabolism to resume but has not yet committed to growth. A seed dried during Phase II can return to dormancy; a seed dried during Phase III cannot — once growth has begun, it is irreversible.

For a chickpea seed at 20 °C in distilled water:

- Phase I lasts about 6 to 8 hours, during which water content rises from about 10% to about 50% (fresh weight basis).

- Phase II lasts about 18 to 24 hours, during which water content stays near 50%.

- Phase III begins after about 30 hours, marked by visible radicle emergence, and continues for several days as the seedling grows.

The transition from Phase II to Phase III is the *commitment point*. Before this point, the seed is reversible. After it, the seed is on its way to becoming a plant.

Respiration rate during germination

The rate of oxygen consumption by a germinating seed can be measured with a simple respirometer (a sealed jar with a CO_2 absorber and a manometer to track pressure change). Typical values for chickpea at 25 °C:

- Dry seed: less than 0.1 µmol O_2 per gram per hour.

- After 12 hours of imbibition: about 5 µmol O_2 per gram per hour.

- After 24 hours: about 30 µmol O_2 per gram per hour.

- After 48 hours (radicle emerged): about 60 µmol O_2 per gram per hour.

The respiration rate rises by roughly three orders of magnitude in two days. This explains why germinating seeds, packed tightly together with poor air circulation, can suffocate themselves — their oxygen demand outstrips supply.

For a sown field at typical sowing density, the oxygen demand is not a problem because the seeds are well separated. But in a seed-soaking vessel, where a kilogram of seed sits in a few litres of water, the dissolved oxygen can be exhausted within hours. This is why farmers who soak seeds before sowing change the water regularly, or do not soak for more than a few hours.

Calculating the energy budget of a seedling

A chickpea seed has a dry mass of roughly 200 mg. Of this, about 60% (120 mg) is carbohydrate, mostly starch. The energy content of carbohydrate is about 17 kJ per gram. So the seed contains roughly 0.12 × 17 = 2 kJ of energy in its food store. There is additional energy in the protein and lipid fractions; the total stored chemical energy is perhaps 3 kJ.

How much of this is used by the seedling before it begins to feed itself?

If the seedling respires at an average rate of 30 µmol O_2 per gram per hour for the first 5 days (120 hours) of germination, total oxygen consumption is:

> 0.2 g × 30 µmol/g/h × 120 h = 720 µmol O_2

Each mole of O_2 consumed in respiration corresponds to about 480 kJ of energy released (since one mole of glucose consumes 6 moles of O_2 and releases 2,870 kJ). So:

> 720 µmol × 480 kJ/mol × 10^{-3} = 0.35 kJ

The seedling uses about 0.35 kJ in the first five days. Compared to the seed's total store of 3 kJ, this is about 10% — much less than I would have guessed before doing the calculation.

But this is only the energy burned in respiration. Much more of the seed's stored food is *converted* into seedling tissue rather than burned. The seedling, after five days, has perhaps doubled the seed's original tissue mass: most of the seed's carbohydrate has been transformed, not respired. The energy of the seed is mostly being used to build, not to burn.

This insight matters. Germination is an investment, not a combustion. The seed is not burning fuel to power motion; it is using its food store as raw material to build a new plant body. The respiration we measure is the running cost of the construction work, not the construction itself.

A model of dormancy

Why does a seed sown in May not germinate, but the same seed sown in November does?

A simple model: the seed contains some amount of dormancy-inducing substance D (a stand-in for abscisic acid and related compounds). D decays exponentially with time at a rate that depends on temperature:

> $D(t) = D_0 \times e^{(-k_T \times t)}$

where k_T is the decay rate at temperature T. The seed will germinate when D falls below a threshold value, given moisture and warmth.

In post-harvest chickpea, D_0 is high — the seed is deeply dormant. Through the dry summer months on the shelf, in warm storage, D decays. By November, D has fallen below threshold for most seeds in the batch, and they will germinate readily when sown.

If you sowed the same seed in May, immediately after harvest, D would still be high. Even with adequate water and warmth, germination would be slow and uneven.

The decay rate kG is temperature-sensitive in a particular way: it is faster at moderate temperatures (20–30 °C) than at very high or very low. This is one of the reasons why seeds stored in moderate conditions lose dormancy faster than those frozen or kept very hot.

This model is rough, but it captures the essence. It also makes a testable prediction: if you measure the germination percentage of a chickpea batch at different times after harvest, you should see an S-curve — low for the first few weeks, rising sharply after some weeks of after-ripening, plateauing at maximum after a few months. Real data look like this. The S-curve is the integral of an exponential decay process.

Temperature and the rate of germination

Within the range of temperatures at which a seed will germinate at all, the rate of germination depends on temperature in a predictable way. For each seed there is a minimum temperature below which germination does not occur, an optimum at which it occurs fastest, and a maximum above which it does not occur. Between minimum and optimum, the rate rises roughly linearly with temperature.

This linear rise can be written:

> Rate = (T − T_min) / θ

where T is the actual temperature, T_min is the minimum (base) temperature for germination, and θ is a constant specific to each seed (in degree-days).

For chickpea: T_min ≈ 5 °C, θ ≈ 60 degree-days to first emergence. At 15 °C, the rate is (15–5)/60 = 0.167 per day, so emergence takes about 6 days. At 25 °C, the rate is (25–5)/60 = 0.333 per day, so emergence takes about 3 days.

For bajra: $T_{min} \approx 12$ °C, $\theta \approx 40$ degree-days. At 25 °C, the rate is (25–12)/40 = 0.325 per day, about 3 days. At 35 °C, (35–12)/40 = 0.575 per day, about 1.7 days.

The base temperature T_{min} is the deep botanical fact. Bajra cannot germinate below 12 °C, no matter how long you wait, because its enzymes do not work at that temperature. Chickpea can germinate at 5 °C but takes a long time. This is why sowing date matters so much: sow chickpea in October when soil is still 28 °C and the seed gets damaged; sow it in November at 18 °C and it germinates in five days, which matches the available soil moisture window.

The degree-day model is widely used in agricultural planning. The growing season for a crop is described by the total degree-days available between sowing and harvest, and varieties are selected to match the available thermal budget. This kind of quantitative crop-climate modelling is the basis of modern agricultural advisories and is increasingly important as the climate shifts.

The seed and the climate question

This last point opens onto a real frontier.

As average temperatures rise across North India — and they have risen by about 0.7 °C over the past century — the windows of suitable conditions for traditional crops are shifting. A chickpea sown in early November now meets warmer soil than it did fifty years ago. The germination is faster, yes, but flowering is also brought forward, and the maturation may run into the heat of March before the pods have filled. Yields can drop even when total seasonal rainfall is unchanged.

Researchers working on this problem are now studying:

The variability in dormancy and germination temperature among traditional varieties (landraces) of chickpea, bajra, mustard, and other crops. Some landraces germinate at higher temperatures than others, and these may be valuable as breeding stock for warmer futures.

The physiology of seed longevity in storage — how seeds maintain viability, how oxidative damage accumulates, and how some seeds (like lotus) can remain viable for centuries while others (like coconut) lose viability within months. Understanding this is critical for seed banks and for preserving genetic diversity.

The interaction between seed germination and soil microbial communities. Recent work has shown that seeds carry their own bacteria and fungi (the *seed microbiome*) and that these influence germination success. The biology of the seed extends, in effect, beyond the seed itself.

Each of these is a live question. The chickpea in your palm, ancient and familiar, is at the centre of research that may decide whether Indian agriculture can adapt to the next half-century of climate change. The seeds that were once given to you by your grandmother may turn out to be the most valuable inheritance she could pass down.

The next chapter goes upward — from the seed below the soil to the leaf above it, where the seedling, having exhausted its inheritance, must begin to make its own food from sunlight, air, and water.

Exercises

Level A — Observation and basic understanding

1. List the three seeds discussed in this chapter, give their Hindi names, and state the season in which each is sown in North India.

2. A chickpea seed is split into three parts. Name and briefly describe each part.

3. Why is a seed called "alive but waiting"? Explain in a few sentences without using technical terms.

4. What is the difference between a monocot and a dicot? Give two examples of each.

5. Describe what happens to a chickpea seed during the first three days after it is placed in moist soil. Use simple drawings if you wish.

6. Why is a seed coat important? What would happen if a seed had no seed coat?

Level B — Mechanism and reasoning

7. Explain the difference between *dormancy* and *quiescence*. Give an example of each.

8. Write the equation for aerobic respiration. Explain how a germinating seed uses this reaction and what it does with the energy released.

9. Name three plant hormones or hormone-like substances that influence germination, and describe the role of each.

10. Why does bajra not germinate well in February in North India, while chickpea germinates excellently in November? Answer in terms of base temperature and seasonal cues.

11. Describe the four stages of germination (imbibition, activation, mobilisation, establishment) and explain what is critical about the transition between Stages 3 and 4.

12. A farmer soaks bajra seed in water for 48 hours before sowing. Many of the seeds fail to germinate after planting. Suggest a biological explanation.

13. Explain why traditional Indian agriculture grows different crops in kharif and rabi seasons. What does this tell us about the origins of these crops?

Level C — Quantitative and exploratory

14. The base temperature for chickpea germination is 5 °C and the thermal time required for emergence is approximately 60 degree-days. Calculate the expected time to emergence at soil temperatures of 12 °C, 18 °C, and 24 °C. Plot the relationship.

15. A chickpea seed of dry mass 200 mg contains approximately 60% carbohydrate by mass. Using an energy content of 17 kJ per gram of carbohydrate, calculate the total chemical energy stored in the seed. Then, given a respiration rate of 30 µmol O_2 per gram per hour for 5 days, calculate the fraction of this energy used in respiration during germination. Discuss what happens to the remainder.

16. Using the exponential decay model of dormancy $D(t) = D_0 \times e^{(-k \times t)}$, suppose $D_0 = 100$ (arbitrary units) and the threshold for germination is $D = 20$. If the decay rate at 25 °C is $k = 0.02$ per day, how many days must the seed be stored before it will germinate readily? How does this compare to the actual after-ripening period of chickpea, which is typically about 2 months?

17. The germination percentage of a batch of chickpea seed, measured monthly after harvest, gives the following data: month 1: 15%; month 2: 40%; month 3: 70%; month 4: 90%; month 5: 95%; month 6: 96%. Plot these data and discuss the shape of the curve in relation to the dormancy decay model.

18. Research project. Soak 30 chickpea seeds in water and 30 in a 5% salt solution. After 24 hours, weigh the seeds and calculate the percentage water uptake for each group. After 5 days, measure germination percentage. Write a short report explaining your findings in terms of osmosis and seed physiology.

19. Open question. The text mentions that seeds carry their own microbes — a *seed microbiome*. Propose an experiment to test whether sterilising seed surfaces (with mild bleach) affects germination rate or seedling

vigour. What would your control be? What would you measure? What would your results mean for traditional seed storage practices?

20. The traditional sowing date for chickpea in Punjab is around the second week of November. If average soil temperature in early November has risen by 2 °C over the past fifty years, what shift in sowing date might be optimal to maintain the same total degree-days from sowing to maturity? What other factors — moisture, day length, post-monsoon weather variability — would complicate this simple adjustment?

Activity — Sprout and watch

Take a handful of chickpea, a handful of mustard, and (if available) a handful of bajra. Soak each overnight in separate cups of water. The next morning, drain the water and place the seeds on damp cotton wool or paper towels in clean dishes. Cover loosely. Keep them at room temperature (or, for bajra, in a warm place).

Observe daily for two weeks. Record:

- Day of first radicle emergence for each species.

- Day of first shoot emergence.

- Length of radicle and shoot daily.

- Differences in seedling appearance.

Compare your results with the descriptions in Pass 2. Which seed germinated fastest? Which produced the longest root in the first week? Which produced the largest first leaf? Use these observations to discuss the trade-offs each species makes in its design.

Chapter

A factory the size of a coin

Walk into the field in late July. The monsoon has arrived three weeks ago. The soil is dark with moisture. The air is heavy. Everything is green — but a different green from the dry green of April. This green is alive, hungry, growing fast.

Look down. At your feet, by the edge of the field, a young bajra plant. It is perhaps a metre tall, with a thick stem and long narrow leaves that arch outward and downward. Pick one of these leaves carefully — bend it at the base, slide it off. Hold it flat across your palm. It is longer than your hand, perhaps thirty centimetres, but only two centimetres wide. The surface is a little rough, slightly hairy. The colour is deep green, with a paler central rib running down the middle. The underside is paler still.

Now walk a few steps to where, in a low corner of the field where water collects, someone has planted arbi — taro — for the kitchen. Its leaves are something else entirely. Each one is heart-shaped, the size of two open hands, smooth and waxy on top. They sit on long stalks held high above the wet ground. Water drops from a recent shower bead on the surface and roll off without wetting it.

Two leaves, growing in the same field, in the same month, fed by the same rain. The bajra leaf is narrow, tough, slightly hairy, facing more or less upward. The arbi leaf is broad, soft, glossy, almost horizontal. One is built for harsh sun. The other is built for shade and damp.

These differences are not decorations. They are answers to questions the plant has been asked by its environment. Each leaf is a factory, and each factory has been designed for a particular set of conditions. To understand a leaf is to understand the problem it is solving.

What problem? The same problem every leaf on every plant on earth is solving. How to take three things — sunlight, water, and carbon dioxide from the air — and combine them to make food.

What a leaf is for

Hold the bajra leaf up to the light. If it is fresh, the light passes through it just a little — you can see your fingers behind it as a vague shadow. Look closely at the surface. It is not perfectly smooth. There are tiny ridges and grooves, and along these ridges, if you had a good hand lens, you would see thousands of small holes. Stomata, they are called — the breathing pores of the leaf.

A leaf takes in carbon dioxide through these pores. Just as you breathe in oxygen through your nose, the leaf breathes in carbon dioxide through its stomata. The carbon dioxide comes from the air — there is a little of it everywhere, about four parts in every ten thousand parts of air. The leaf pulls it in.

A leaf also lets water out through these same pores. Water arrives in the leaf from the soil, drawn up through the roots and up the stem, through tiny pipes that run from the roots all the way to the tips of the leaves. When the stomata are open to let carbon dioxide in, water vapour escapes out. This is unavoidable. On a hot dry day, a single bajra plant may lose several litres of water through its leaves. On a small farm, the total water lost by all the plants together is enormous. We will return to where this water goes later — for now, just notice: the leaf must trade water for carbon dioxide. Every breath in is also a breath out.

And the leaf takes in sunlight. This needs no special pore. The light simply falls onto the leaf and is absorbed by the green pigment inside the cells. The pigment is called *chlorophyll*. It is what makes a leaf green — but more importantly, it is what catches the energy of the sun.

So: sunlight from above. Carbon dioxide from the air. Water from the soil. These three meet inside the leaf, in cells full of chlorophyll, and a reaction takes place that has no equivalent anywhere else in the living world.

The energy of sunlight is captured. It is used to drive a chemical reaction that joins carbon dioxide and water together to make sugar. The sugar is the food the plant uses to grow. As a by-product, oxygen is released, and it escapes from the stomata into the air.

This is *photosynthesis*. We met its equation in Chapter 1, and we will look at it more carefully in Pass 2. For now, hold the idea: the green leaf is a small chemical factory, powered by sunlight, that makes food from air and water. Every plant on the farm is doing this. Every plant on earth is doing this. Every animal alive — including you — is alive because of food that originally came from photosynthesis in a leaf.

Why leaves are different shapes

If photosynthesis is the same chemistry in every leaf, why are bajra leaves narrow and arbi leaves broad?

Consider the bajra plant. It grows in fields where the sun beats down for ten hours a day from a sky often cloudless even in monsoon. The summer temperatures it experiences can reach 40 °C or more. It must conserve water — the monsoon is generous now but the soil dries fast in heat, and the deep dry season is never far away. A narrow leaf has a small surface for catching sun, yes, but it also has a small surface for losing water. The vertical orientation — leaves arching down rather than spread out flat — means that at noon, when the sun is overhead and the heat is greatest, the leaves present only their edges to the sun. They cook less. Less water is lost. The plant survives.

The arbi, by contrast, grows in shade — under trees, in damp low corners of fields, in the wet margins of ponds and ditches. Where it lives, light is scarce, not water. A broad horizontal leaf can catch every photon that filters through the canopy. The plant cannot afford to waste any light. Water is everywhere, so losing some through the broad leaf is not a problem.

The waxy coating on the arbi leaf has a different purpose. It is not for keeping water in — it is for keeping water *off*. A heavy rain on a thin, soft leaf can split it, or weigh it down, or wash off dust and pollen the plant needs. The wax makes the leaf surface so smooth that water beads up and rolls away in seconds, taking dust with it but leaving the leaf intact. Watch a fresh arbi leaf in rain and you can see water gather into perfect silver beads that race across the surface and tumble off the edge. Engineers have studied this surface — the *lotus effect* — to design self-cleaning paints and water-repellent coatings.

The hairs on the bajra leaf serve yet another purpose. They reduce the airflow right at the leaf surface. In dry windy conditions this slows the rate at which water vapour escapes from the stomata: the hairs trap a thin layer of still humid air against the leaf, like a shield. They also reflect some sunlight, reducing heat load. A young bajra leaf can have so many hairs that it looks silvery in early morning light.

Each leaf, then, is shaped by the climate of its home. Walk through any Indian field at any time of year, and you can read the climate in the leaves. Thick, waxy, narrow leaves: dry conditions. Broad, thin, soft leaves: moist conditions. Leaves with many fine divisions and silver hairs: deserts. Leaves with deep red undersides: low-light forests. The diversity is enormous, but the principles are few.

The flow of food

Now follow what happens after the leaf has done its work.

The sugar made in the leaf does not stay in the leaf. The leaf needs only a small amount for itself. The rest must travel to where it is needed — to the growing tip of the stem, to the young flowers, to the roots reaching down for more water, to the developing seeds.

Inside the leaf, and throughout the plant, there are two sets of pipes. One set carries water and dissolved minerals from the roots upward to the leaves. This set is called the *xylem*. The other set carries sugars and other organic substances from the leaves to wherever the plant needs them. This set is called the *phloem*. The xylem flows up; the phloem flows wherever sugar is needed — usually down toward the roots, but also up to growing shoots, and outward to fruits and seeds.

Together these two sets of pipes are called the *vascular system* of the plant. You can see them in a leaf if you look carefully. The central rib of a bajra leaf — the pale green stripe down the middle — contains the main vascular bundles. Smaller side veins branch off, and from these, yet smaller veins, and finally the network reaches every cell. No cell in a leaf is more than a few cells away from a vein.

If you snap a stalk of arbi cleanly and look at the cut end, you can see the vascular bundles as a ring of small dots, each one a tiny pipe. In a young bajra stem, the bundles are scattered through the tissue rather than arranged in a ring — this is one of the differences between monocots and dicots that we met in the seed chapter.

The plant, then, is plumbing as well as factory. Each leaf is a factory making sugar; the stem is the highway distributing it. The whole structure of a plant — roots below, stem rising, leaves branching out — is built around the logistics of moving water up and food down, all at once.

A day in the life of a leaf

Imagine following a bajra leaf for a single day in late July.

At sunrise, around 5:30 in the morning, the leaf is cool. Its stomata are closed; the air is humid and there is no urgent reason to open them. Photosynthesis is not yet running.

As the sun rises, light reaches the chlorophyll inside the cells. The leaf warms. The stomata begin to open. Carbon dioxide flows in from the air. Water, drawn up through the xylem from the soil, fills the leaf and begins to evaporate from the cells lining the stomata. Photosynthesis begins.

By mid-morning, the leaf is in full production. The stomata are wide open. Carbon dioxide is being absorbed and turned into sugar at a rapid rate. The sugar flows out through the phloem to the rest of the plant. The plant is growing.

By noon, the sun is fierce. The air temperature has reached 35 °C. The leaf is also losing water rapidly — perhaps a teaspoon-worth in an hour, just from this one leaf. If the soil is still wet from a recent rain, the plant can keep up. The water flows up from the roots fast enough to replace what is lost. The stomata stay open. Photosynthesis continues.

But if the soil has dried — say, this is a hot day at the end of August, and there has been no rain for ten days — then by noon the plant cannot keep up with water loss. The leaf begins to dry. To prevent damage, the plant closes its stomata. Photosynthesis stops, or slows to a trickle. Sugar production halts. The plant waits.

By late afternoon, as the sun drops, the heat eases. The stomata may reopen for a few hours. Some afternoon photosynthesis happens. By sunset, the stomata close again. Night photosynthesis is impossible because there is no light. The day's work is done.

In the dark hours, the leaf continues to respire — to burn some of the day's sugar to keep its cells alive. The plant as a whole continues to grow, drawing on the day's stored sugars, sending them to the growing parts. The plant does not sleep. It just stops making new sugar, and lives on what it made during the day.

Tomorrow, if the sun rises again on a leaf with water in its veins, the cycle resumes.

What the farmer sees

The farmer who walks through the field knows none of this in textbook terms. But the farmer reads leaves all the time.

A bajra leaf that is pale yellow rather than deep green: the plant is short of nitrogen. There is not enough nitrogen in the soil to build chlorophyll, and a leaf without chlorophyll is a leaf that cannot make food.

A leaf that droops at midday but recovers by evening: the plant is short of water in the heat of the day but is finding enough at night. The farmer may need to irrigate.

A leaf that has purple edges: the plant is short of phosphorus, or has been chilled. The colour is a stress signal — anthocyanin pigments accumulating in damaged cells.

A leaf with brown spots: a fungal infection. A leaf with chewed edges: an insect. A leaf curled inward: aphids may be hiding underneath. Each pattern, each colour, each shape change is a message the plant is sending. The farmer who can read these messages knows the field. The farmer who cannot will miss the early warnings and the season will go badly.

The leaf, then, is a factory, a chemical reactor, a hydraulic system, a heat exchanger, and — to the careful observer — a diary of the plant's experience.

In the next pass, we open the leaf and look at what happens inside the chloroplast: the actual chemistry of photosynthesis, the difference between the way bajra does it and the way wheat does it, and why this difference matters for Indian farming.

Pass 2 — The Mechanism

Inside the leaf

A leaf, in cross-section, has three main layers.

The *upper epidermis* is a single layer of flat, transparent cells on the top surface. It is covered by a waxy coat — the *cuticle* — that prevents water loss. This wax is what makes the arbi leaf shed water; in tougher leaves like the mango or the babul, the cuticle is so thick that the leaf can survive long droughts.

The *mesophyll* is the middle layer. This is where photosynthesis happens. In most plants the mesophyll has two sublayers: an upper *palisade* layer of column-shaped cells densely packed with chloroplasts (the green

organelles that contain chlorophyll), and a lower *spongy* layer of loosely packed cells with air spaces between them. The palisade catches the most light; the spongy layer allows gases to circulate.

The *lower epidermis* is a single layer on the bottom surface. In most leaves it is here that the stomata are concentrated — sometimes thousands per square centimetre. Each stoma is bordered by two crescent-shaped *guard cells* that can swell or shrink to open or close the pore.

Running through the mesophyll are the veins — bundles of xylem and phloem, surrounded by supporting tissue. The veins are the leaf's plumbing.

Now: the chloroplast. Each mesophyll cell may contain forty or fifty of these. Each chloroplast is a small ovoid body, perhaps five micrometres across. Inside it are stacks of flat membrane sacs called *thylakoids*, arranged like piles of coins (each pile is a *granum*; the spaces between piles are connected by membrane sheets called *stroma lamellae*). Embedded in the thylakoid membranes are the molecules of chlorophyll, and a great many proteins that work together to do the actual chemistry of photosynthesis.

Outside the thylakoid stacks, but still inside the chloroplast, is a fluid called the *stroma*. This is where the other half of photosynthesis happens — the part that does not require light directly, but that builds the actual sugar molecules.

The whole leaf, then, is a layered system optimised for one task: bring water in through the xylem, bring carbon dioxide in through the stomata, catch light in the chloroplasts, and pump sugar out through the phloem.

The two halves of photosynthesis

The reaction we wrote in Chapter 1:

> $6\,CO_2 + 6\,H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6\,O_2$

is a summary. The actual process happens in two stages, in two different parts of the chloroplast.

The light reactions happen on the thylakoid membranes. They begin when a photon of light is absorbed by a chlorophyll molecule. The energy of the photon excites an electron in the chlorophyll to a higher energy state. This excited electron is then passed along a chain of proteins in the thylakoid membrane (this chain is called the *electron transport chain*), and in the process its energy is used to do two things:

First, to split water molecules into hydrogen ions, electrons, and oxygen. The oxygen is released as a by-product — this is the source of nearly all the oxygen in earth's atmosphere. (Take a breath. Most of the oxygen molecules in your lungs were produced by photosynthesis somewhere on earth, at some point in the past several years. Almost every breath you have ever taken contains atoms of oxygen released by leaves.)

Second, to produce two energy-carrying molecules called *ATP* and *NADPH*. These are not sugar — they are short-lived energy currencies that carry the captured solar energy from the thylakoid out into the stroma, where the next stage uses them.

The dark reactions (or, more accurately, the *light-independent* reactions, or the *Calvin cycle* after the chemist who worked them out) happen in the stroma. They take carbon dioxide from the air and combine it with a 5-carbon sugar already present in the stroma (called RuBP) to make two 3-carbon molecules (called 3-PGA). This is the *carbon fixation* step, and the enzyme that does it is called *Rubisco* — possibly the most abundant protein on earth.

Then, using the ATP and NADPH from the light reactions, the 3-PGA molecules are progressively rearranged and combined to make a 6-carbon sugar — glucose. Some of the carbon also goes back to regenerating RuBP, so the cycle can continue. For every six molecules of CO_2 that enter the cycle, one molecule of glucose is produced and six new molecules of RuBP are regenerated.

The two halves are coupled. The light reactions cannot proceed indefinitely without the dark reactions, because ATP and NADPH must be consumed to make room for new ones. The dark reactions cannot proceed at all without the light reactions, because there is no other source of ATP and NADPH. Light and dark together make a continuous process — but only the light reactions need light.

The problem of Rubisco

Here is a complication that turns out to matter enormously for Indian farming.

Rubisco — the enzyme that fixes carbon dioxide in the Calvin cycle — evolved billions of years ago, when the earth's atmosphere was very different from today. The atmosphere then had much more carbon dioxide and almost no oxygen. Rubisco was good at grabbing CO_2 from a CO_2-rich atmosphere.

Today, the atmosphere is the opposite. Oxygen is plentiful (21%); CO_2 is scarce (0.04%). And Rubisco, in this new environment, makes a mistake. About a quarter of the time, instead of grabbing CO_2 and adding it to RuBP, Rubisco grabs O_2 and does the opposite — it tears RuBP apart. This is called *photorespiration*, and it is a waste of the plant's resources. The plant gets less sugar out of its leaf than it should.

Photorespiration gets worse in hot weather. As temperature rises, oxygen becomes relatively more abundant in solution inside the leaf, and CO_2 less so. By the time leaf temperature reaches 35 °C — a typical summer afternoon in much of India — photorespiration may consume thirty or forty percent of the carbon the plant has fixed. The plant works hard but loses ground.

This was a serious problem for plants growing in tropical heat. So, over the past 30 million years, some plants evolved a workaround.

C4 photosynthesis: bajra's solution

Bajra, jowar (sorghum), maize, sugarcane, and several other tropical crops do photosynthesis differently from chickpea, mustard, rice, wheat, and most temperate plants. They use a system called *C4 photosynthesis*, and it is one of the great inventions of plant evolution.

In ordinary photosynthesis (called *C3* because the first product of carbon fixation is a 3-carbon molecule), all the work happens in the same cells: mesophyll cells take in CO_2, do the light reactions, do the Calvin cycle, make sugar. Rubisco is doing all the work, and it is exposed to all the atmospheric oxygen in the leaf.

In C4 photosynthesis, the work is split between two cell types. The mesophyll cells, on the outside of the leaf, take in CO_2 through a different enzyme (PEP carboxylase) that does not confuse CO_2 with O_2. This enzyme adds CO_2 to a 3-carbon molecule (PEP) to make a 4-carbon molecule (oxaloacetate, then malate) — hence the name *C4*.

The 4-carbon molecules are then transported into a special ring of cells around the veins, called *bundle sheath* cells. In these cells, the 4-carbon molecules are broken down to release CO_2. This CO_2 is now concentrated inside the bundle sheath cells, far away from atmospheric oxygen. Rubisco, working in the bundle sheath, is fed a high-CO_2 environment and almost never makes the photorespiration mistake.

The result is that C4 plants can photosynthesise efficiently even in conditions of high temperature and high light — exactly the conditions of an Indian summer. They use water more efficiently than C3 plants. They produce more biomass per unit of water and per unit of nitrogen. They are, in short, designed for tropical agriculture.

This is why bajra can grow in places where wheat cannot. Wheat is C3: in the heat of late May and June in Punjab, wheat would suffer enormously, and it does — the wheat harvest must finish by April before the heat sets in. Bajra, sown in June, thrives in heat that would destroy wheat.

The list of C4 crops is short but important: maize, sugarcane, sorghum (jowar), pearl millet (bajra), finger millet (ragi), and several wild grasses that are major weeds. The list of C3 crops is longer: rice, wheat, barley, oats, all the legumes (chickpea, tur, moong, urad, soybean), all the cucurbits (cucumber, gourds, melons), all the brassicas (mustard, cabbage, cauliflower), most fruits, and almost all trees.

The C4 advantage is not absolute. C3 plants are more efficient at lower temperatures, in shade, and at high CO_2 concentrations. This is why wheat and rice grow well in cool weather but bajra does not, and why C3 plants dominate in temperate climates while C4 plants dominate in the tropics and subtropics.

Stomata: the trade-off

Every leaf, C3 or C4, faces the same fundamental trade-off. To do photosynthesis, the leaf must open its stomata to let CO_2 in. But every time the stomata are open, water vapour escapes. The hotter and drier the air, the more water is lost per unit of CO_2 gained. A plant that opens its stomata wide grows fast but loses water fast. A plant that keeps its stomata nearly closed loses little water but grows slowly.

C4 plants resolve this trade-off slightly more efficiently than C3 plants. Because their PEP carboxylase pulls CO_2 from the air faster than Rubisco does, they can keep their stomata only partly open and still get enough CO_2. This reduces water loss. A C4 plant typically loses about half as much water per gram of sugar produced as a C3 plant.

But there is a third way, used by some tropical succulents (cacti, many of the *Crassulaceae*, pineapple, agave): CAM photosynthesis, or *Crassulacean Acid Metabolism*. CAM plants keep their stomata closed during the day and open them only at night. They take in CO_2 in the cool night air, store it as malic acid in their cells, and then in the daytime they break down the malic acid to release CO_2 for Rubisco — all with the stomata closed. The water savings are enormous, but the productivity is low: a CAM plant grows very slowly.

CAM is rare in agriculture but not absent. Pineapple is CAM. Agave is CAM. The dragon fruit (*pitaya*) now being grown in some Indian states is CAM. They are all crops adapted to extremely dry conditions where their slow growth is acceptable because faster crops would fail entirely.

C3, C4, CAM. Three solutions to the same problem. The diversity of plants on a farm reflects the diversity of solutions evolution has found.

Where does the sugar go?

The leaf is the source of sugar. But sugar is needed everywhere in the plant. How does it move?

In the leaf, sugar produced by the Calvin cycle is loaded into the phloem cells of the veins. This is an active process — it costs energy — because the sugar must move against its concentration gradient. The phloem cells become extremely sugar-rich.

Water then flows from the xylem (which carries dilute mineral solution from the roots) into the phloem by osmosis. The high sugar concentration in the phloem pulls water in. The phloem cells, being now very full of sugary fluid, develop high pressure.

This pressure pushes the phloem fluid along the pipe, away from the leaf, toward wherever the sugar is being used. At the destination — say, a developing seed, or a growing root tip — the sugar is unloaded into the cells that need it. Water leaves the phloem at this end, the pressure drops, and the cycle continues.

The mechanism is called *pressure flow*. It was proposed in 1930 by the German plant physiologist Ernst Münch, and it remains the standard model. The pressures involved are real and measurable — typically one to two atmospheres in the phloem of an actively photosynthesising leaf. If you make a fresh cut into the phloem

of certain plants (sugarcane, for example), the phloem fluid actually squirts out under pressure. This is why aphids, which feed on phloem, do not need to suck — the plant's own pressure pushes the sap into the aphid.

The phloem can move sugar in any direction the plant needs. In spring, sugar flows up from the roots to the buds. In summer, sugar flows down from the leaves to the roots and stored organs. In autumn, sugar flows from the leaves to the developing seeds. The direction is set not by gravity but by the gradient of demand: wherever sugar is being consumed fastest, that is where the phloem flows.

Linking back to Chapter 1

We can now close a loop.

In Chapter 1, the compost heap was breaking plant material apart — running respiration on tissue that had once been alive, releasing CO_2 to the air, leaving humus in the soil. We noted there that the compost heap was the reverse of photosynthesis: where photosynthesis builds glucose from CO_2, water, and light, respiration tears glucose apart back into CO_2 and water.

In this chapter, we have looked at the building side. The leaf is taking CO_2 from the air and water from the soil and using sunlight to build the molecules that, eventually, will end up in next year's compost heap. The carbon atoms that are now in the bajra plant's leaves were, three weeks ago, in the atmosphere. Some of them, in three months, will be in the grain. Some, in six months, will be in the soil. Some, in a year, will be back in the atmosphere as the plant's residues decompose.

The compost heap and the leaf are two ends of the same conveyor belt. Together they make the carbon cycle of the farm.

In Pass 3, we will measure this cycle quantitatively — how much carbon a hectare of bajra fixes in a season, how much water it loses, how much energy it captures from the sun, and how this compares to a wheat field, a tur field, and a forest. We will also look at how rising atmospheric CO_2 and rising temperatures are changing the balance for Indian crops.

Pass 3 — The Mathematics and the Frontier

The energy budget of a leaf

A square metre of bajra canopy in clear July sunlight in North India receives a power of roughly 800 to 1,000 watts in incoming solar radiation. The atmosphere has filtered out much of the ultraviolet and a fair amount of the infrared: what reaches the leaf is about half visible light and half near-infrared.

Of this incoming radiation, only the visible portion can drive photosynthesis. The infrared simply warms the leaf without contributing to chemistry. Of the visible light, perhaps eighty percent is absorbed by the leaf (some is reflected, some passes through). Of the absorbed light, only a fraction is captured by chlorophyll in a useful form, and only a fraction of that ends up driving carbon fixation.

The maximum theoretical efficiency of photosynthesis — the fraction of incoming solar energy that ends up as chemical energy in sugar — is about 11% for a C4 plant and about 9% for a C3 plant. But this is a theoretical ceiling that no real plant approaches. Real efficiencies, integrated over a whole growing season for a whole field, are typically:

- About 1.5% for a healthy C4 crop (maize, bajra, sugarcane).
- About 0.8% for a healthy C3 crop (wheat, rice).
- About 0.3% for an average forest, integrated over the year.

These look small, but they translate to large amounts of biomass. A hectare of bajra in a good season produces about 5 to 6 tonnes of dry matter (grain plus stalks plus roots). A hectare of wheat in Punjab might produce 8 tonnes including straw. Sugarcane, on a long growing cycle, can produce 30 to 40 tonnes of dry biomass per hectare per year.

Quantifying the trade-off: water use efficiency

How much water does a plant lose to make a unit of sugar?

The standard measure is *water use efficiency* (WUE): grams of biomass produced per kilogram of water transpired.

Typical values:

- C3 plants (wheat, rice, chickpea): 2 to 4 g biomass per kg water.

- C4 plants (bajra, maize, sorghum): 4 to 8 g biomass per kg water.

- CAM plants (pineapple, agave): 10 to 20 g biomass per kg water.

In practical terms: to produce one kilogram of wheat grain, a wheat plant must transpire roughly 500 to 800 litres of water. To produce one kilogram of bajra grain, a bajra plant transpires perhaps 250 to 400 litres. To produce one kilogram of pineapple flesh, an agave-like plant might transpire as little as 100 litres.

These numbers translate directly to irrigation needs. The transition in the 1960s and 1970s, in much of North India, from traditional bajra and jowar to irrigated wheat and rice was, in water terms, a major commitment. The wheat-rice rotation of Punjab and Haryana uses 1,500 to 2,000 millimetres of water per hectare per year. The traditional bajra-chickpea rotation used 400 to 700 millimetres. Aquifer depletion in North India is the direct hydrological consequence of this transition. The C4 crops were not abandoned because they were inefficient — quite the opposite — they were abandoned because the high-yielding wheat and rice varieties of the Green Revolution were C3, and irrigation made the water cost seem affordable. As aquifer levels fall and energy costs rise, the question of whether C4 crops should return to a larger share of Indian agriculture is being asked again, seriously.

A photosynthesis rate calculation

How much CO_2 does a leaf fix in a given time?

A healthy bajra leaf in good conditions can fix CO_2 at a rate of about 30 to 50 µmol per square metre per second. Call it 40 µmol/m²/s on average.

Over a 12-hour day, with photosynthesis running at near-maximum for perhaps 8 hours (the rest being early morning, late afternoon, or midday closure), total CO_2 fixed per square metre is:

> 40 µmol/m²/s × 8 hours × 3600 s/hour = 1.15 mol CO_2 per square metre per day

Converting to mass: one mole of CO_2 is 44 grams, but the relevant figure is carbon, which is 12 grams per mole. So:

> 1.15 × 12 = 14 grams of carbon fixed per square metre per day

Translated to sugar (glucose, 30 grams per mole of carbon equivalent):

> Roughly 35 grams of sugar produced per square metre per day under good conditions

Over a 90-day growing season with sufficient water and nutrients:

> 90 days × 35 g/m² = 3.15 kg sugar per square metre

Times 10,000 m² per hectare:

> 31.5 tonnes of sugar-equivalent per hectare per season

But this is gross production — the leaf's chemistry. The plant respires a substantial fraction of this back, perhaps 40%, to power its own growth and maintenance. Net production after respiration is about 18 to 20 tonnes per hectare of sugar-equivalent dry mass.

Real bajra yields are lower — about 6 tonnes per hectare of total dry mass in good conditions, of which 2 to 3 tonnes is grain. The gap between the theoretical maximum and the realised yield is the result of many factors: leaf area is not always 100% covering the ground; stomata close at midday in heat; some leaves are shaded; pests, diseases, and nutrient deficiencies reduce performance; not all days are clear and full of sun.

The gap is the agronomist's territory. Closing it — through better varieties, better timing, better water management, better nutrition — is what crop improvement is all about. There is room, in principle, for

substantially higher yields than current averages. There is no biological reason bajra cannot yield 4 to 5 tonnes per hectare of grain. The reasons it does not are practical and economic, not photosynthetic.

The leaf area index

A plant's photosynthetic capacity depends not only on the rate per leaf but also on the total area of leaf it has. The standard measure is the *Leaf Area Index* (LAI): the total leaf area per unit of ground area.

A bare field has LAI = 0. A young bajra crop at 3 weeks might have LAI = 0.5. A mature bajra canopy fully covering the ground might have LAI = 3 to 4 (each square metre of ground is shaded by three to four square metres of leaf, layered above it).

Photosynthesis per unit of ground area rises with LAI — more leaf area, more photosynthesis — but only up to a point. Above LAI ≈ 3, the lower leaves are too shaded by the upper ones to photosynthesise efficiently. Adding more leaves brings diminishing returns. There is an optimum LAI for each crop in each light environment, and a major part of agronomy is matching plant spacing, sowing density, and variety to achieve this optimum.

This is the quantitative form of the question we touched on in Chapter 1 — the ratios of seed spacing. Too widely spaced, and LAI stays below optimum: total photosynthesis per hectare is less than it could be. Too densely spaced, and the plants shade each other, individual yields drop, and disease pressure rises. The optimum is a balance, and it depends on water, nutrients, and the variety in question.

A note on rising CO_2

The atmosphere of the earth, when this chapter is being written, contains about 425 parts per million of carbon dioxide — up from about 280 parts per million before industrial burning of fossil fuels began. It is rising at about 2.5 parts per million per year.

What does this mean for crops?

For C3 plants, rising CO_2 is mostly beneficial in the short term. Higher atmospheric CO_2 partially overcomes Rubisco's confusion with oxygen: photorespiration is reduced. C3 plants in elevated CO_2 tend to grow faster

and use water more efficiently. This effect is called *CO_2 fertilisation*, and it has been measured in many experiments.

For C4 plants, rising CO_2 matters less. C4 plants already concentrate CO_2 at Rubisco through their own pump: they were not waiting for atmospheric CO_2 to rise. They get some benefit, but much less than C3 plants.

So one might think: rising CO_2 is good for wheat and rice and chickpea, less good for bajra. And in pure photosynthesis terms, this is roughly right.

But there are complications. Rising CO_2 comes with rising temperatures, and rising temperatures are bad for almost all crops once they exceed certain thresholds. The optimum temperature for wheat grain-filling is about 18 °C; at 25 °C, the grain is smaller and the yield drops. The optimum for rice is about 26 °C; above 32 °C, fertility drops. Bajra and maize tolerate higher temperatures but have their own limits.

In addition, elevated CO_2 tends to reduce the protein content of grain. Wheat, rice, and other staples grown in high CO_2 tend to have less nitrogen and less protein per kilogram. The food may be more abundant but less nutritious.

The full picture, then, is mixed. Crops will respond to rising CO_2 and rising temperatures in complicated ways that vary by region, by variety, by management. The research is active and the predictions are still uncertain. But one robust conclusion is emerging: traditional varieties, including landraces and minor crops like bajra, jowar, and the smaller millets, may be better suited to the warmer, more variable climates of the coming decades than the high-yielding C3 varieties of the Green Revolution. The wisdom of the seeds — discussed in Chapter 2 — is increasingly seen as a resource worth protecting.

An open question

Why has C4 photosynthesis evolved many times independently — in grasses, in some succulents, in some forbs — but only ever in a few percent of plant species? Why have so few crop plants gone the C4 route?

Part of the answer is that C4 is more complicated. It requires two cell types with distinct biochemistry, a specific leaf anatomy (the *Kranz* anatomy, with bundle sheath cells), and a coordinated set of additional

enzymes. Evolving all of these together is a large step. C4 has independently evolved in plants more than sixty times, which suggests that the step is doable — but it has not happened in many of the staple crop families.

A major research effort, ongoing for two decades now, is trying to engineer C4 photosynthesis into rice. The *C4 Rice Project* aims to introduce the C4 traits into rice in order to improve its water use efficiency and yield, especially in the hot tropics. The project has shown that some of the key enzymes can be transferred and made to work in rice cells. The anatomical changes — the Kranz arrangement — are harder. Whether a true C4 rice will exist within the next decade or two is unknown. If it does, it would be one of the largest single advances in crop biology of this century.

This is the kind of question that opens up when you take a leaf seriously: what is possible, what is fundamental, what evolution has done and what humans can now do on top of evolution. The bajra leaf in your palm, simple and ordinary, is an example of a solution evolution found that scientists today are still trying to copy.

In the next chapter, we go downward — from the leaf above the soil to the root within it, where the same plant draws water and minerals from the underground world, and where, in legumes like moong and tur, an even older partnership with bacteria provides nitrogen that no leaf could ever capture from the air.

Exercises

Level A — Observation and basic understanding

1. Describe three differences between a bajra leaf and an arbi leaf, and explain how each difference suits the leaf to its environment.

2. What is a stoma? Where is it found, and what does it do?

3. Name the three things a leaf needs to do photosynthesis and where each one comes from.

4. What is chlorophyll? Why is it important?

5. Explain in your own words what happens inside a leaf on a summer day from sunrise to sunset.

6. Why does a plant wilt in the afternoon and recover at night?

Level B — Mechanism and reasoning

7. Describe the layered structure of a leaf in cross-section. Name each layer and state its main function.

8. Write the equation for photosynthesis. Explain in two or three sentences what the equation actually means in terms of the chemistry happening inside a chloroplast.

9. Explain the difference between the light reactions and the dark reactions of photosynthesis. Where in the chloroplast does each happen?

10. What is photorespiration? Why is it a problem, and why is it worse in hot weather?

11. Explain how C4 photosynthesis differs from C3 photosynthesis. Give two examples of C3 crops and two examples of C4 crops.

12. Why can bajra grow well in the June heat of Rajasthan, while wheat sown at the same time would not survive? Answer in terms of plant biology, not just climate.

13. Explain the trade-off between photosynthesis and water loss. Why is this trade-off the central problem every leaf must solve?

14. Sketch the basic structure of the leaf vascular system. Show where the xylem and phloem are, what each carries, and in which direction.

Level C — Quantitative and exploratory

15. A bajra leaf receives 800 W/m² of solar radiation at midday. If the photosynthetic efficiency over a full season is 1.5%, calculate the rate of energy capture per square metre and convert to grams of sugar produced per hour (assuming sugar contains about 17 kJ/g of chemical energy).

16. A field of bajra has a Leaf Area Index of 3.5. If each square metre of leaf fixes carbon at a rate of 30 µmol/m²/s during 8 productive hours per day, calculate the total carbon fixed per square metre of ground per day. Convert to grams of dry biomass per hectare per season (90 days).

17. The water use efficiency of bajra is approximately 6 g of biomass per kg of water transpired, while that of wheat is approximately 3 g/kg. For each crop, calculate the total water required to produce 5 tonnes per hectare of biomass. Compare with typical irrigation amounts for wheat (1,500 mm) and bajra (400 mm) and discuss the discrepancy.

18. Research project. Build a simple leaf transpiration experiment: take three leaves of different species (e.g. bajra, arbi, and a third of your choice). Weigh each, then place them in a sealed clear plastic bag with a small dish of water. Weigh again after 1 hour, 2 hours, and 4 hours. Calculate the rate of water loss per square centimetre of leaf area. Compare with predictions based on leaf type and surface.

19. Open question. The text discusses the C4 Rice Project. Suppose you were given the task of engineering a C4 trait into chickpea, an important C3 legume. List the biological challenges you would face, and explain which you think would be the hardest. Consider both biochemistry (enzymes) and anatomy (leaf structure).

20. The Green Revolution shifted Indian agriculture toward irrigated C3 crops (wheat and rice). If India faces increasing water scarcity and rising temperatures over the next 50 years, what biological argument could you make for restoring a larger share of C4 crops (bajra, jowar, ragi, maize) to the cropping system? What economic, social, and dietary changes would be required to support this shift?

Activity — Watch a leaf breathe

Take a healthy potted plant (or a young plant in your school garden) on a warm sunny morning. Tie a clean clear plastic bag tightly around one leaf, taking care not to damage the leaf or seal in extra moisture. Leave it for 30 minutes in sunlight.

Observe: water droplets should appear on the inside of the bag. This is water vapour transpired from the stomata.

Try the experiment again, this time after gently coating the underside of the leaf with petroleum jelly (which blocks the stomata). Repeat with the upper surface coated instead. Compare the three results.

Where are most of the stomata located in this plant? How do you know? Write up your observations and connect them to the structure of the leaf described in Pass 2.